GEORGIA INSTITUTE OF TECHNOLOGY
OFFICE OF RESEARCH ADMINISTRATION

RESEARCH PROJECT INITIATION

Date: November 27, 1973

Project Title: Excitation & Ionization of Ions by Electron Impact

Project No: E-21-635

Principal Investigator Dr. R. K. Feeney

Sponsor: Atomic Energy Commission, Oak Ridge Operations

Agreement Period: From 9/1/73 Until 8/31/74

Type Agreement: Modification No. 12 to Contract No. AT-(40-1)-3027

Amount: $43,303 AEC Funds (E-210635)
16,274 GIT Contributions (E-21-324)
$59,577 Total Estimated Cost

Reports Required:
Publication Preprints; Publication Reprints; Progress Report; Final Report

Sponsor Contact Person (s):

Mr. Earl Mason
Research Contracts, Procedures & Reports Branch
Contract Division, U. S. Atomic Energy Commission
Oak Ridge Operations
P. O. Box E
Oak Ridge, Tennessee 37830
Phone: (615) 483-8611

NOTE: Follow-on to E-21-623

Assigned to: School of Electrical Engineering

COPIES TO:

Principal Investigator	Library
School Director	Rich Electronic Computer Center
Dean of the College	Photographic Laboratory
Director, Research Administration	Project File
Director, Financial Affairs (2)	
Security-Reports-Property Office ✓	
Patent Coordinator	Other

RA-3 (6-71)

GEORGIA INSTITUTE OF TECHNOLOGY

OFFICE OF RESEARCH ADMINISTRATION

RESEARCH PROJECT TERMINATION

Date: 18 September 1975

Project Title: Excitation & Ionization of Ions by Electron Impact

Project No: E-21-635

Principal Investigator: Dr. R. E. Feeney

Sponsor: Atomic Energy Commission

Effective Termination Date: 8/31/74

Clearance of Accounting Charges: All clear

Grant/Contract Closeout Actions Remaining: None

NOTE: Continued as Project E-21-649

Assigned to School of ~~Electrical Engineering~~

COPIES TO:

- Principal Investigator
- School Director
- Dean of the College
- Director of Research Administration
- Office of Financial Affairs (2)
- Security - Reports - Property Office
- Patent and Inventions Coordinator
- Library, Technical Reports Section
- Computer Sciences
- Photographic Laboratory
- Terminated Project File No. _____
- Other _____

E-21-635

GEORGIA INSTITUTE OF TECHNOLOGY, ATLANTA, GEORGIA Statement of Annual Costs

U.S. ATOMIC ENERGY COMMISSION

1. Name and address of Contractor: Georgia Institute of Technology
   Atlanta, Georgia 30332

2. Contract number: AT-(40-1)-3027

3. Beginning and ending date of pertinent contract period: September 1, 1973 through August 31, 1974.

4. Costs incurred during the pertinent contract period:

a.	Salaries and wages	$28,670.46
b.	Equipment (see attachment)	4,178.07
c.	Travel (all domestic)	496.81
d.	Other direct costs	7,449.67
e.	Total direct expenditures	$40,795.01
f.	Indirect charges (65% of S & W)	18,635.80

5. Total costs for the pertinent contract period $59,430.81

6. Support cost for the pertinent contract period. Using the percentage of 72.7% as set forth in Appendix "A" the amount chargeable to the AEC would be $43,206.20 (72.7% of $59,430.81). However, only $43,156.51 has been charged to the AEC account. We prefer that the difference of $49.69 be treated as unexpended and available for expenditure during the subsequent contract period. $43,156.51

7. Cumulative support cost $199,789.41

8. Accumulated support ceiling 203,844.00

9. Unexpended AEC funds $ 4,054.59

I hereby certify that this report is true and correct to the best of my knowledge and belief and that the costs listed herein were incurred in connection with the performance of the research provided for under this contract and in accordance with the terms and conditions set forth therein.

Robert K. Feeney, Assistant Professor of Electrical Engineering
Name and title of principal investigator

Signature _____ 6 Dec 74
Date

Evan Crosby, Associate Director of Financial Affairs

Signature _____ 12/10/74
Date

Attachment

EQUIPMENT

AEC CONTRACT AT-(40-1)-3027
CONTRACT YEAR SEPTEMBER 1, 1973 - AUGUST 31, 1974

Quantity	Description	Amount
1	Veeco Instruments Inc. RG83/TG7110/50/160 Linear Ion Gauge with accessories	$615.00
1	Sorenson model DCR300-18A power supply	1,780.00
1	Varian special 6-port vacuum cross fitting	1,083.31
1	Varian special 6-inch tee fitting	699.76
		$4,178.07

E-21-635

REPORT NO. ORO-3027-23
Technical Progress Report
Project No. E-21-635

Covering the Period
Sept. 1, 1973 to May 31, 1974

The Excitation and Ionization of Ions By Electron Impact

By R. K. Feeney
T. F. Divine
J. W. Hooper
R. M. Kovac
D. McPherson
W. E. Sayle

Contract No. AT-(40-1)-3027

U. S. ATOMIC ENERGY COMMISSION
OAK RIDGE, TENNESSEE
31 May 1974

School of Electrical Engineering
GEORGIA INSTITUTE OF TECHNOLOGY
Atlanta, Georgia

REPORT NO. ORO-3027-23

PROJECT NO. E-21-635

THE EXCITATION AND IONIZATION OF IONS BY ELECTRON IMPACT

By

R. K. Feeney
T. F. Divine
J. W. Hooper
R. M. Kovac
D. McPherson
W. E. Sayle

COVERING THE PERIOD

September 1, 1973 to May 31, 1974

CONTRACT NO. AT-(40-1)-3027

U. S. Atomic Energy Commission
Oak Ridge, Tennessee

May 31, 1974

TABLE OF CONTENTS

Report No. ORO-3027-23, Project E-21-635

I. Title

The Excitation and Ionization of Ions by Electron Impact

II. Period Covered by Report

The period covered by this report is September 1, 1973 to May 31, 1974. This corresponds to the first nine months of the twelve month extension provided by Modification No. 12 of Contract No. AT-(40-1)-3027.

III. Project Abstract

This report covers four different but closely related experimental programs. These are (a) absolute measurements of the cross sections for the ionization of Tl^+, Cs^+, and Rb^+ ions by electron impact over the range of incident electron energies from below threshold to approximately 2000 eV; (b) the determination of the absolute cross sections for input excitation by electrons with energies from near threshold to 5-20 times threshold of electric dipole transitions for the 2^3S - 2^3P multiplet in the helium-like B^{2+} and C^{3+} ions; (c) the refinement and extrapolation of the experimental techniques used in (b) so as to facilitate the determination of electron impact excitation cross sections for additional members of the helium and lithium isoelectronic sequences; (d) an investigation of the aluminosilicate thermionic-type ion sources for use in collision experiments; and (e) use of previously developed magneoplasma transient response apparatus to measure the momentum elastic scattering cross sections for electrons in argon gas. Item (d) is undertaken as a subpart of (a) while item (e) represents a terminal activity under this program but is included to illustrate typical results and usefulness of the technique.

IV. Ionization of Tl^+, Cs^+, and Rb^+ Ions by Electron Impact

The ion beam probe is proving to be an extremely versatile and valuable plasma diagnostic tool. Probes can measure plasma density, space potential, charge and current desnity, electric and magnetic fields, and electron temperature.[1-15] The technique permits plasma parameters to be resolved both in space and time. Ion beam probes have been applied to several machines including Elmo,[6,8] Doublett II,[13] UARL Baseball,[14] the ST Tokamak,[2] and ORMAK.[6] In addition, probe specifications for use with future CTR devices and, ultimately fusion reactors, are being developed.[15]

The majority of operating probes have employed alkali or thallium ions in the probe beam.[1-14] The validity of results obtained with the

---

[1] R. L. Hickok and F. C. Jobes, AFOSR TR-70-2354 (1970).

[2] R. L. Hickok and F. C. Jobes, AFOSR TR-72-0018 (1972).

[3] F. C. Jobes and R. L. Hickok, Nucl. Fusion, 10, 195 (1970).

[4] F. C. Jobes, J. F. Marshall, and R. L. Hickok, Phys. Rev. Letters, 22, 1042 (1969).

[5] R. E. Reinovsky, W. C. Jennings, and R. L. Hickok, Phys. Fluids, 16, 1772 (1973).

[6] G. S. McNeilly, ORNL-4834 (1973).

[7] P. Couture and B. L. Stansfield, Bull. Am. Phys. Soc., 18, 1276 (1973).

[8] C. E. Bush, loc. cit. 18, 1276 (1973).

[9] G. X. Kambic, loc. cit. 18, 1276 (1973).

[10] R. E. Reinovsky, W. C. Jennings, and R. L. Hickok, loc. cit. 18, 1276 (1973).

[11] W. C. Jennings, J. C. Glowienka, and R. E. Reinovsky, loc. cit. 18, 1276 (1973).

[12] J. C. Glowienka, R. E. Reinovsky, and R. L. Hickok, loc. cit. 18, 1276 (1973).

[13] G. S. Huchital, W. C. Jennings, and R. L. Hickok, loc. cit. 18, 1276 (1973).

[14] J. M. Stufflebeam, W. C. Jennings, and R. L. Hickok, loc. cit. 18, 1277 (1973).

[15] R. L. Hickok, R. E. Reinovsky, and W. C. Jennings, loc. cit. 18, 1277 (1973).

techniques is dependent upon the accuracy of the appropriate ionization cross sections. This is particularly true of electron temperature measurements.[5] The require electron impact ionization cross sections are available for Li^+, Na^+, and K^+, but have not yet been published for Rb^+, Cs^+, and Tl^+ ions.[16-19] The present work has concentrated on providing these latter three cross sections. Included in this report are preliminary measured cross sections for the ionization of Tl^+ ions from threshold to 2000 eV, and the ionization of Cs^+ ions from 200 to 2000 eV. These data will be given following a discussion of the experimental method and apparatus.

The experimental method involves crossing pulsed (or dc) beams of singly charged ions and electrons in a well defined collision volume. Proper account is taken of the relative velocity of the two beams. There are no appreciable electric or magnetic fields in the interaction region. Therefore, all of the projectile ions, including those which undergo reaction either with the electron beam or the background gas molecules travel essentially the same trajectory until the beam is separated into its various charge states after passing through the interaction region. Measurement of the final beams yields the ionization cross section provided that the effects of the background gas are eliminated. Several review papers critically discuss the charged particle-charged particle crossed

---

[16] W. C. Lineberger, J. W. Hooper, E. W. McDaniel, Phys. Rev. 141, 151 (1966).

[17] J. W. Hooper, W. C. Lineberger, and F. M. Bacon, Phys. Rev. 141, 165 (1966).

[18] B. Peart and K. T. Dolder, J. Phys. B 1, 872 (1968).

[19] B. Peart and K. T. Dolder, J. Phys. B 1, 240 (1968).

beam technique.[16,17,21-23]

The present measurements have been accomplished in a completely rebuilt and refined version of a previously used apparatus.[16,17,20] The new apparatus, which is shown schematically in Figure, and in plan view in Figure 2 will now be briefly described.

Singly charged ions are produced by a thermionic-type ion source and pass through several focusing, collimating, and deflecting structures before entering the interaction region. A rectangular electron beam intersects the ion beam at right angles and is collected by the electron Faraday cup. After undergoing collisions with the electrons, the ion beam, which now contains several charge states, passes into the guarded parallel plate electrostatic analyzer. Here the various charge states are separated and diverted to their respective Faraday cups. The spatial densities of the beams are sampled prior to the interaction region by simultaneously scanning both beams with an L-shaped probe having coplanar slits. This scanner is driven from outside the vacuum chamber by a stepping motor sequenced by a preset counter.

The thermionic-type ion source has many advantages when used in collision experiments. Such sources are simple in construction, produce no large gas load, and give moderate current densities with long lifetime.

---

[20] R. K. Feeney, J. W. Hooper, and M. T. Elford, Phys. Rev. A 6, 1469 (1972).

[21] G. H. Dunn, in Atomic Physics, edited by B. Bederson, V. W. Cohen, and F. M. J. Pichanick (Plenum, 1969), pp. 417-433

[22] M. F. A. Harrison, Brit. J. Appl. Phys. 17, 371 (1966).

[23] K. T. Dolder, in Case Studies in Atomic Collision Physics, Vol. I, edited by E. W. McDaniel and M. R. C. McDowell (North Holland, 1969), Ch. 5.

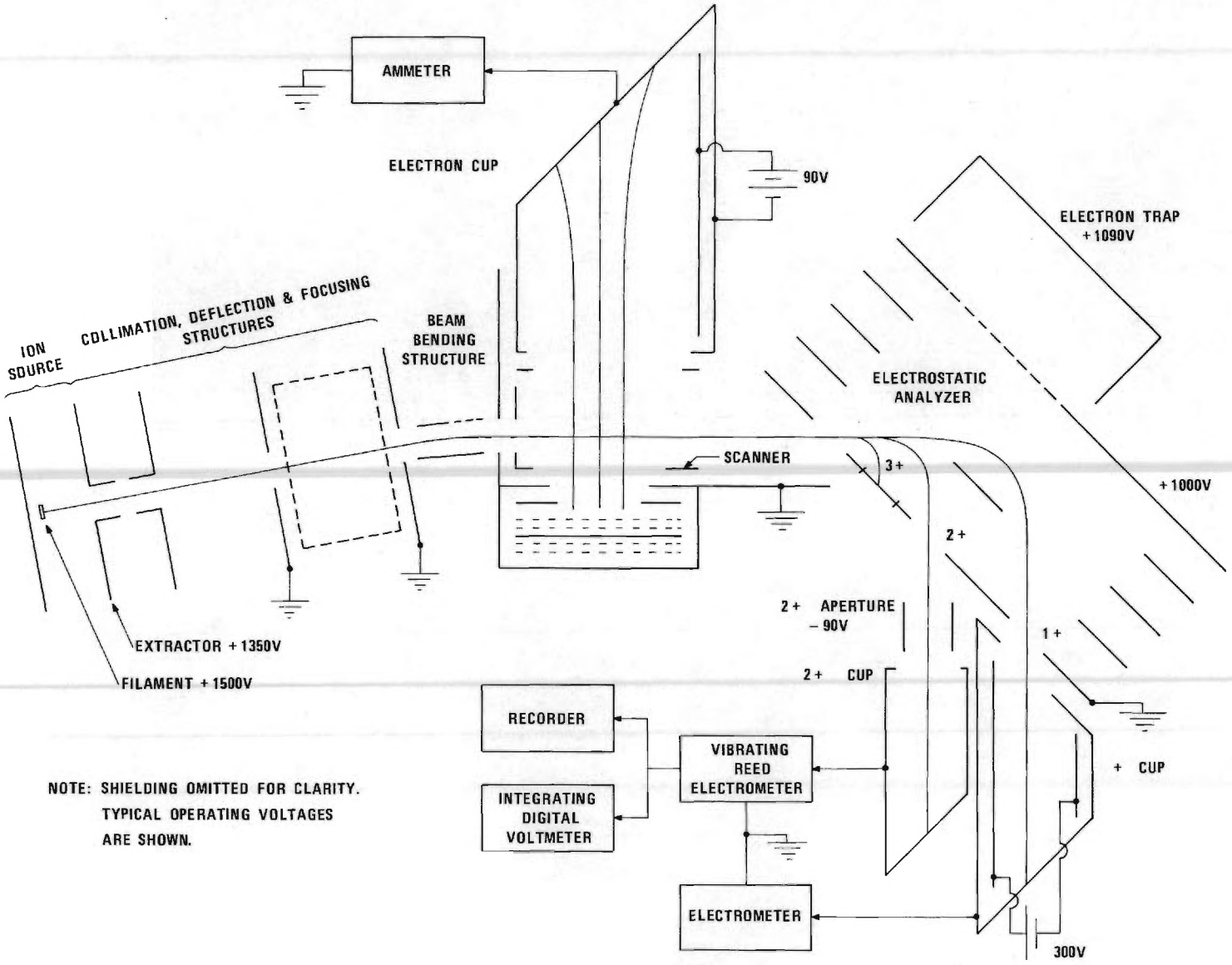

Figure 1. Schematic Diagram of the Ionization Apparatus.

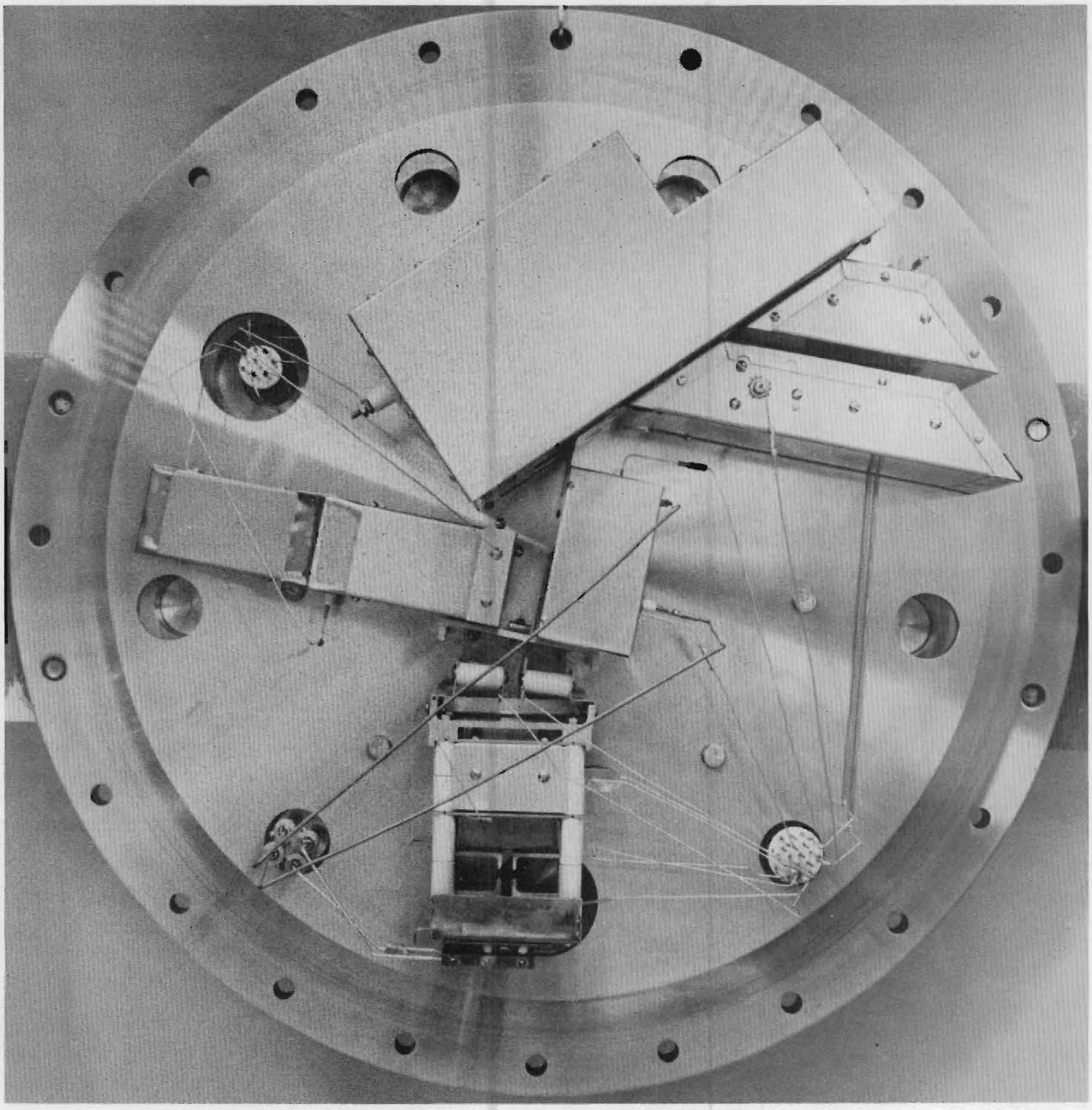

Figure 2. Plan View Photograph of the Ionization Experiment.

Of greater significance is the lack of metastable states produced in the source. We have used the thermionic sources in our previous studies of the alkali ions,[16,17] and in the present thallium work. Our appreciation of the unique properties of these thermionic emitters has led to a systematic investigation of them. A summary of this work is included in this report.

In this experiment, as in our earlier work[16,17,20] a 6L6 beam tetrode was first used as an electron source. As indicated in the last Progress Report,[24] some difficulty was experienced in getting the oxide cathode to reliably activate. This difficulty was attributed to the presence of small quantities of thallium vapor in the vacuum system. To alleviate this difficulty with a minimum of engineering changes in the experimental apparatus, a thoriated iridium filament was substituted for the original oxide cathode. A spring was installed to keep the filament in proper position within the beam forming structure. In order to avoid an unacceptably large electron energy spread, it was necessary to pulse the electron filament heating current as was done in our recent excitation experiment.[25] In this pulsing scheme, electrons are withdrawn from the heated filament only when the voltage across the filament is zero. Thus, only thermal spread should be present in the beam. Although our previous work[25] indicated that the energy spread of this type of electron source is quite low, it has not been experimentally verified for this particular installation. An energy analyzer has been constructed and will be employed

---

[24] R. K. Feeney, T. F. Divine, J. W. Hooper, D. McPherson, and W. E. Sayle, The Excitation and Ionization of Ions by Electron Impact, Report No. ORO-3027-19, Georgia Institute of Technology, Atlanta, Georgia (1973).

[25] M. O. Pace and J. W. Hooper, Phys. Rev. A 6, 2033 (1973).

with the source in the near future.

The direcly heated electron source can be operated without modification to the 6L6GC tube structure up to about 1000 eV. Above 1000 eV, it is necessary to slightly change the source arrangement by the addition of an extractor electrode. In this manner we have operated the source up to 2000 eV with no difficulty, and should be able to go to 10 keV if such were desired.

The ion and electron beam pulsing scheme is similar to that used previously by several investigators.[16-20] In the present experiment, the extractor electrode is used to pulse the ion beam and the control grid is used to pulse the electron beam. Properly synchronized signals are generated by digital electronics followed by transistor buffer amplifiers.

As described in a previous report,[24] the refined apparatus incorporates many improvements including a guarded electrostatic analyzer, improved shielding of Faraday cups, and a magnetic "electron trap" located at the entrance to the doubly charged ion cup. With these improvements, the electron current background has been reduced sufficiently so as to allow measurement of desired cross sections out to greater than 2 keV electron energy.

In addition to the capability of the measurement of single ionization events, the present experiment can also determine the cross sections for reactions of the form,

$$e + X^{+} \rightarrow e + X^{3+} + 2e \ .$$

However, due to space restrictions within the apparatus[24] the two processes

cannot be observed simultaneously. It is planned to measure the double ionization processes upon completion of the present work.

Figure 3 gives the experimentally determined Tl^+ electron impact ionization cross sections. These results include both the preliminary data obtained with the "old" apparatus[20] as well as those determined with the refined apparatus. Both the oxide and directly heated cathodes were used in the new experiment. Altogether two apparatus and two different electron sources were used. There was no systematic variation of the experimental data, and results made with all combinations of apparatus and sources agree to within the estimated experimental error. Typical conditions of operation were: Tl^+ ion beam energy, 1.0-1.5 keV; Tl^+ ion beam current, 1-10 $\times$ 10^{-8} A; Tl^+ ion beam duty cycle, 40%; electron beam current, 20-300 μA; electron beam duty ccyle, 50%; and form factor, 0.5-0.7 cm. Error bars enclose the maximum experimental scatter plus an estimated $\pm$ 7% maximum systematic error. An estimated 2 $\pm$ 1 eV energy degradation due to the oxide cathode has been applied to those data; the directly heated emitter should have no significant degradation. However, since the directly heated electron source has not yet been studied with an energy analyzer, the Tl^+ ionization data are regarded as PRELIMINARY. Final data will be published when available.

Figure 4 gives the experimentally determined Cs^+ electron impact ionization cross sections. All of these data were taken with the refined apparatus using the directly heated electron source. Typical operating conditions were similar to those used for Tl^+. These data will be extended to the low energy regime after completion of the electron source energy spread measurements. For the same reason stated in conjunction

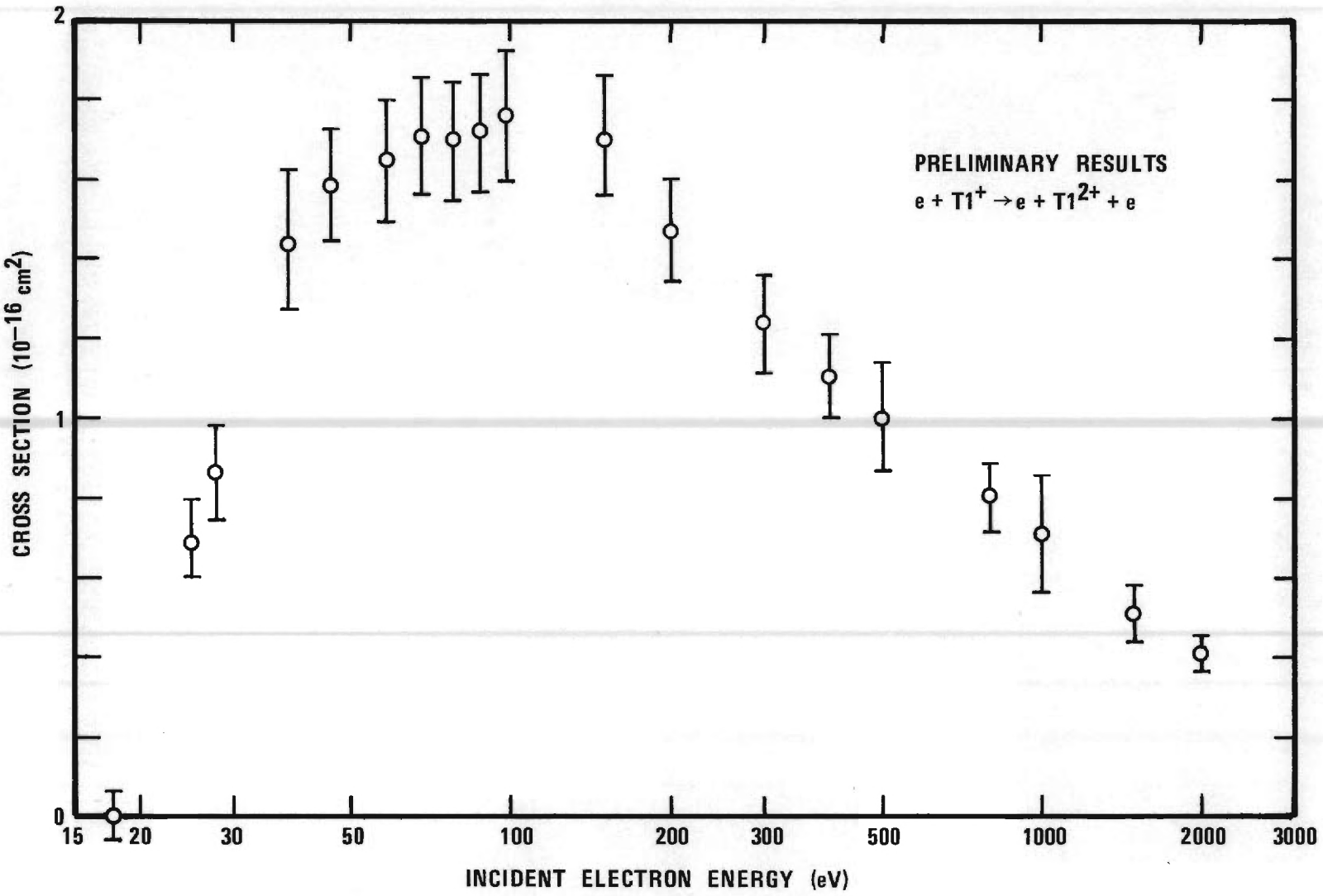

Figure 3. Absolute Experimental Cross Sections for the Ionization of Tl^+ Ions by Electron Impact.

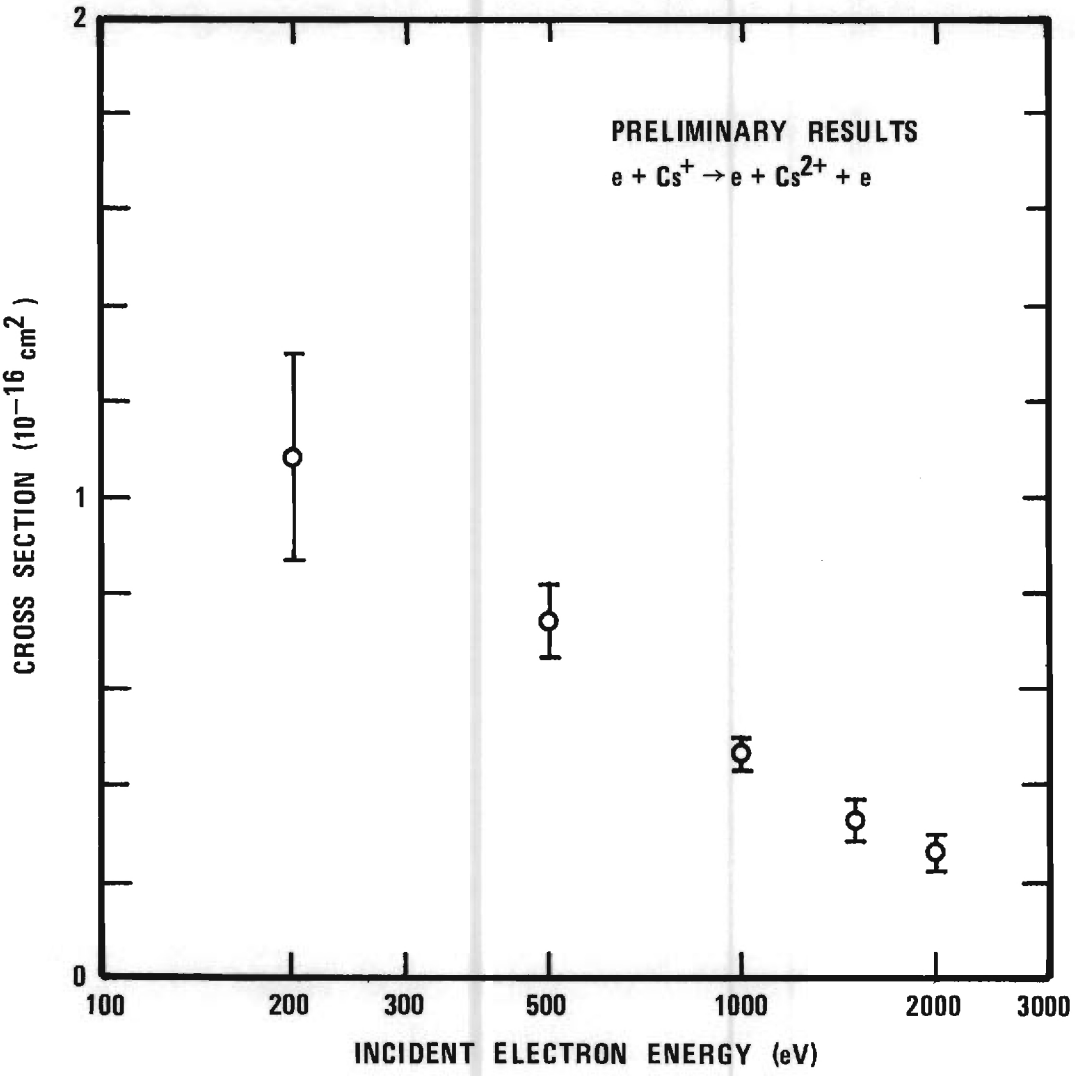

Figure 4. Absolute Experimental Cross Sections for the Ionization of Cs^+ Ions by Electron Impact.

with the Tl^+ data, these results should be considered PRELIMINARY.

V. Thermionic Sources of Positive Ions

Typical charged-particle--charged-particle collision experiments require stable, long-lived ion beams of known excitation state. The complexity of such experiments is reduced when the ion sources involved do not require differential pumping. Thermionic-type sources have been found to be ideal in the above respects.

The emission and lifetime characteristics of six types of filament emitters were evaluated for use as positive ion sources in the crossed beam experiments. Preparation of Li^+, Na^+, K^+, Rb^+, Cs^+, and Tl^+ emitters followed the procedures used by Blewett and Jones[26] and Allison and Kamegai[27] which involve the reaction

$$X_2CO_3 + Al_2O_3 + 4SiO_2 \Rightarrow X_2O \cdot AlO_3 \cdot 4SiO_2 + CO_2\uparrow$$

In this equation X is the desired element. The filaments were prepared by alternate painting and heating of the emitting compound on a Pt-Rh gauze strip.

Each filament was individually characterized by measuring temperature as a function of filament current for two samples of each emitter type in a bell jar vacuum system. The two samples were then evaluated in two long-term tests. One filament was installed in a mass spectrometer system for analysis of specific ion emission as a function of time while the second filament was placed in the bell jar for measurement of

---

[26] J. P. Blewett and E. J. Jones, Phys. Rev. 50, 465 (1936).

[27] S. K. Allison and M. Kamegai, Rev. Sci. Instr. 32, 1090 (1961).

its gross emission current as functions of applied electric field and temperature.

Each type of emitter was evaluated for a period of approximately 100 hours in the mass spectrometer. The electric and magnetic fields were varied to determine which ions were being emitted, according to the relationship

$$m = K \frac{B^2}{V} \qquad (1)$$

where m is the atomic mass number, B is the magnetic flux density, V is the acceleration potential difference and K is a constant. The presence of the mass 41 isotope of potassium was used for positive identification of K^+ and as an aid in identification of other elements using equation (1).

The currents of specific ions emitted by each filament were measured periodically over the duration of the test. Table 1 shows the types of impurities present in each emitter and the approximate operating time required before the impurity concentration is below 1%.

Table 1. Impurity Characteristics

Filament	Impurities	Minimum time for impurities < 1%
$^6Li^+$ (isotopically purified)	Na^+, K^+	< 26 hrs.
Na^+	K^+, Cs^+	< 22 hrs.
K^+ (Georgia Feldspar)	Na^+	< 3 hrs.
Rb^+	K^+	< 0.3 hrs.
Cs^+	K^+	< 1 hr.
Tl^+	Na^+, K^+	< 0.8 hr.

The sepcific ion emission of the Rb^+ filament is shown in Figure 5. While the information presented in Table 1 and Figure 5 represents typical behavior of this class of filament emitters, it must be considered qualitative in nature. The behavior is repeatable but variations in filament construction (especially thickness) and changes in the filament temperature during the tests preclude absolute comparisons of emission performance.

After installation in the bell jar vacuum system, the total ion current was periodically measured for each emitter as a function of filament temperature for three different extraction voltages. Table 2 shows the typical gross current densitites obtainable from the six ion emitters at an approximate operating temperature of 1000° C for an extraction voltage of 500 V. The filament operating time is also shown and for each filament this time is greater than the time for which impurity ion emission is less than 1%.

Table 2. Cross Current Densities

Filament	Time on Filament	Approximate Gross Current Density (at 1000° C)
$^6Li^+$ (isotopically purified)	69.5 hrs.	1.7×10^{-6} A/cm^2
Na^+	79.5 hrs.	1.1×10^{-4} A/cm^2
K^+ (Georgia Feldspar)	61.5 hrs.	2.0×10^{-5} A/cm^2
Rb^+	29.3 hrs.	1.4×10^{-4} A/cm^2
Cs^+	20.8 hrs.	1.1×10^{-4} A/cm^2
Tl^+	68.3 hrs.	2.6×10^{-6} A/cm^2

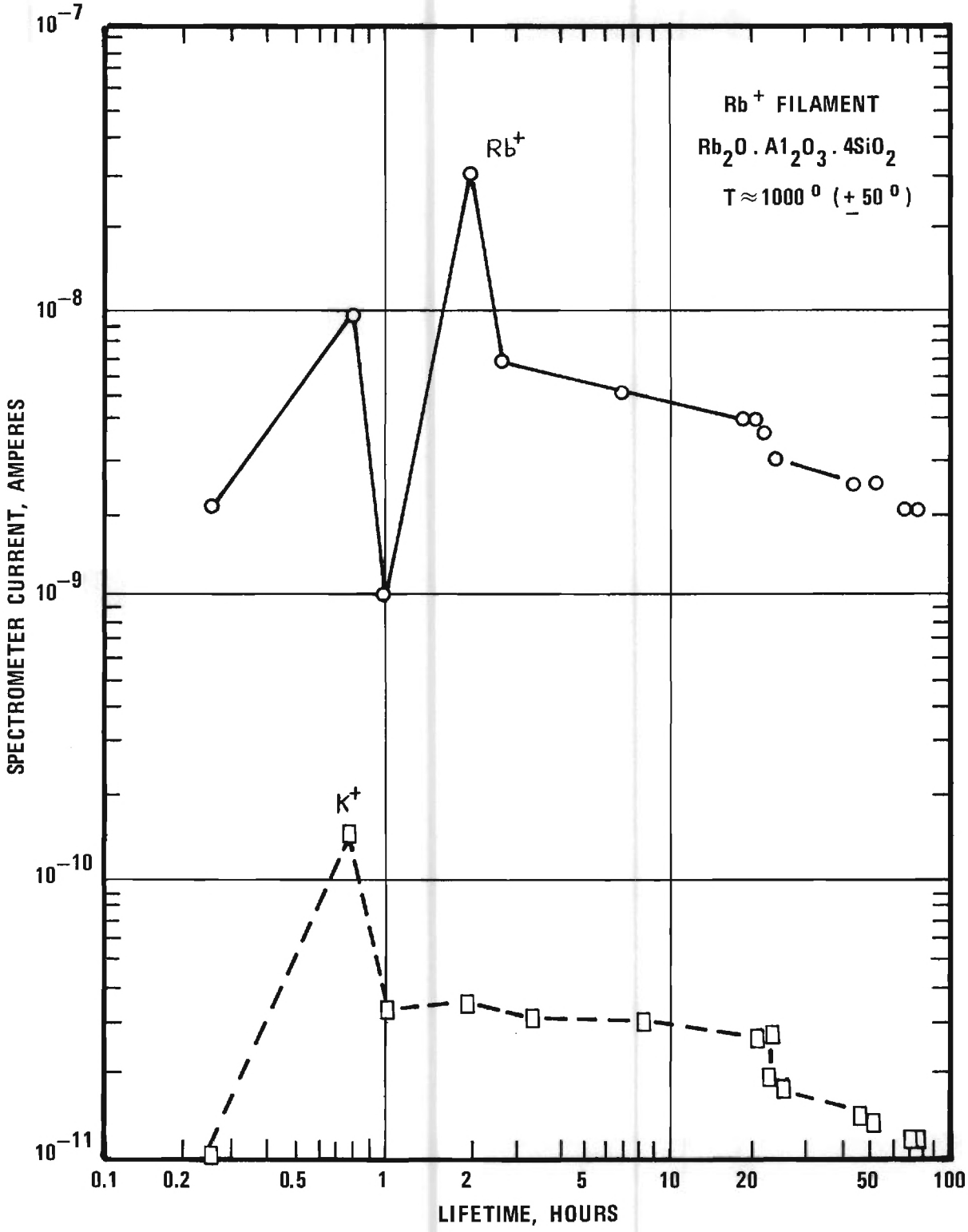

Figure 5. Impurity Characteristics of the Rb^+ Ion Thermionic-Type Emitter.

From Table 2 it is apparent that the Li^+ and Tl^+ emitters produce significantly less current density, by some two orders of magnitude, than the other emitters.

Positive ion sources constructed using the procedures outlined in this section are suitable for use in crossed beam experiments. The typical source lifetimes of several hundred hours and the relatively short time for reduction in the impurity levels to below 1% are especially attractive.

VI. Excitation of Helium- and Lithium-Like Ions

This effort is devoted to the design, development, and construction of apparatus and perfection of techniques leading to ultimate measurements of the electron impact excitation cross sections of multiply charged ions. The helium- and lithium-like ions are expected to play a major role in future diagnostics of high temperature plasmas. Spectroscopic methods can provide information as to the electron temperature, electron density, and ion density as well as impurity densities and losses.[28-33] Almost all such techniques require knowledge of one or

---

[28] I. M. Podgornyi, Topics in Plasma Diagnostics, (Plenum Press, New York, (1971).

[29] R. H. Huddleston and S. L. Leonard, Plasma Diagnostics, (Academic Press, New York, 1965).

[30] R. C. Elton in Methods of Experimental Physics, edited by H. R. Griem and R. H. Lovberg, (Academic Press, New York, 1970) Ch. 4.

[31] L. Heroux, Proc. Phys. Soc. (London) 83, 121 (1964).

[32] R. V. Williams and S. Kaufman, Proc. Phys. Soc. (London) 75, 329 (1960).

[33] H. J. Kunze, A. H. Gabriel, and H. R. Griem, Phys. Fluids, 11, 662 (1968)

more collision cross sections. Measured cross sections for electron impact excitation of multiply charged ions are presently unavailable. Consequently, most plasma workers have relied upon semiempirical[34-35] methods for excitation rate determinations together with a few Born-type calculations.[36-39]

It is planned to measure the electron impact excitation cross sections using the crossed beam technique.[25,] This method for excitation measurement is basically similar to that used for ionization, but no post interaction region charge state analyzer is needed. The emitted photons are detected by a photomultiplier tube after passage through appropriate wavelength selective filters. One could convert the ionization apparatus shown in Figure 1 to an excitation experiment by positioning a photon selector/detector in a plane above the interaction region.

It would be elegant to simultaneously measure excitation and ionization cross sections in a single apparatus, but as stated in the previous report[24] such will not be done and separate facilities will be used. However, both experiments can function in the same vacuum chamber

---

[34] M. J. Seaton, in Atomic and Molecular Processes, edited by D. R. Bates (Academic Press, New York, 1962) Ch. 11.

[35] H. van Regemorter, Astrophys. J. 136, 906 (1963).

[36] D. P. Sural and N. C. Sil, Proc. Phys. Soc. (London) 87, 201 (1966).

[37] O. Bely, Proc. Phys. Soc. (London) 88, 587 (1966).

[38] O. Bely, Ann. Astrophys. 29, 683 (1966).

[39] P. G. Burke, J. H. Tait, and B. A. Lewis, Proc. Phys. Soc. (London) 87, 209 (1966).

and hence can be attached to the multiply charged ion source.

The experimental apparatus to be used in the excitation cross section measurements is shown schematically in Figure 6. Ions are produced in the P.I.G.-type ion source mounted in the first vacuum chamber. This source, which is undergoing testing, is water cooled and operates at 2-3 A and 0.5-1 kV. A suitable source gas is admitted to the source through a regulator and a leak valve. Because the lifetime of the P.I.G. cathodes is expected to be insufficient to complete a measurement, a high vacuum gate valve is provided to isolate the source from the remainder of the vacuum system. This will allow replacement of the ion source without recycling the entire vacuum system. Figure 7 shows a photograph of the ion source and its associated vacuum system. The arc power supply is the "soft" type commonly used with such sources and employs a high voltage plate transformer in conjunction with solid state diodes and a suitable current limiting impedance.

Upon extraction from the ion source, the ions will be accelerated to 3 keV and subjected to m/e analysis with a 60^{o} magnetic sector spectrometer. The sector will be differentially pumped to maintain a pressure of about 1×10^{-5} Torr. The selector magnet will be supplied from a power supply which can be remotely programmed to maintain a constant magnetic field. After m/e analysis, the desired ion will be focused and deflected by structures situated in two additional vacuum chambers. Differential pumping will be provided so that the ultimate pressure in the collision chamber can be in the low 10^{-8} Torr range. The beam emerging from the ion production and selection system is designed to be approximately 2×10mm in size.

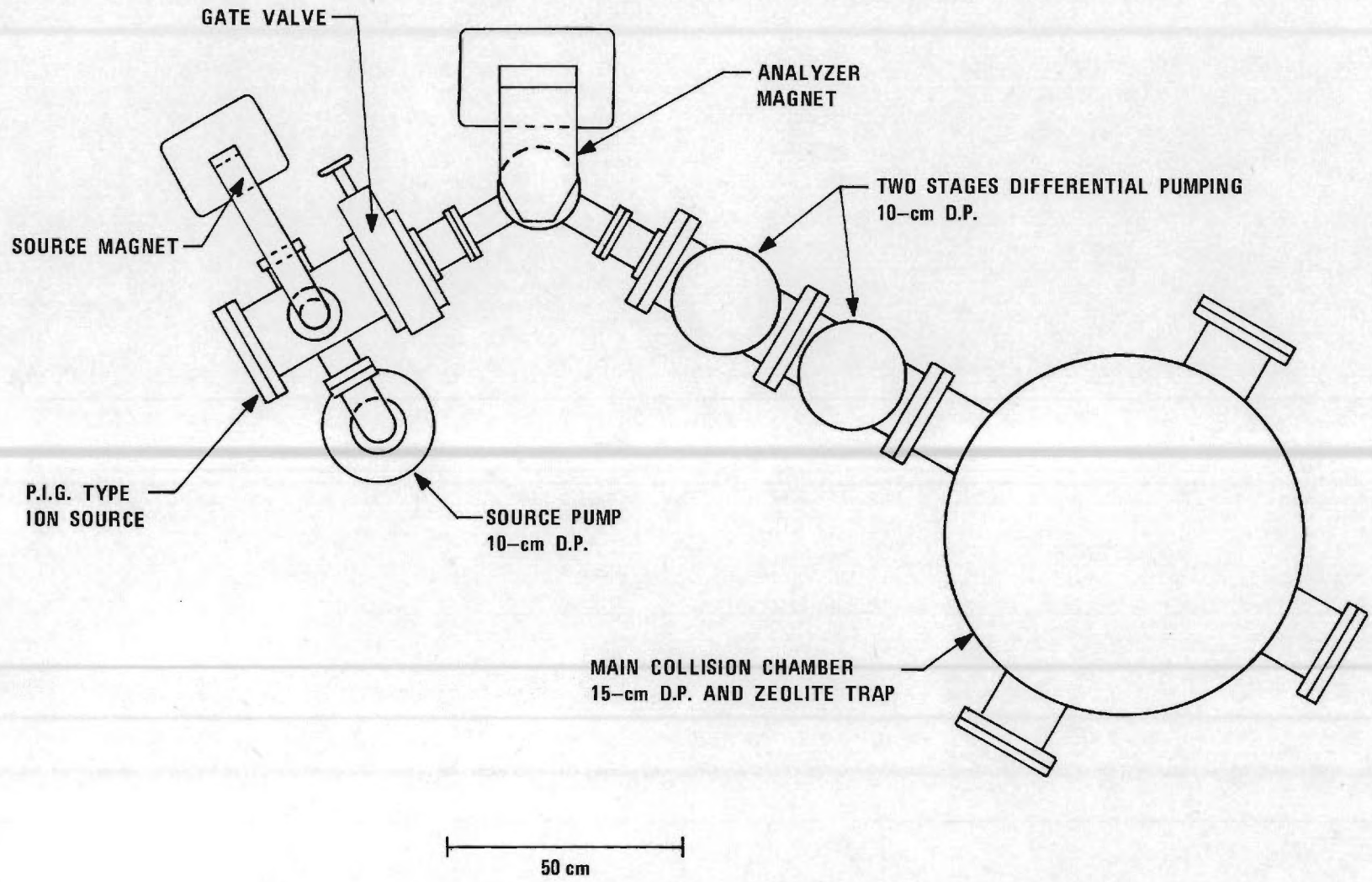

Figure 6. Schematic Drawing of the Multiply Charged Ion Excitation Apparatus.

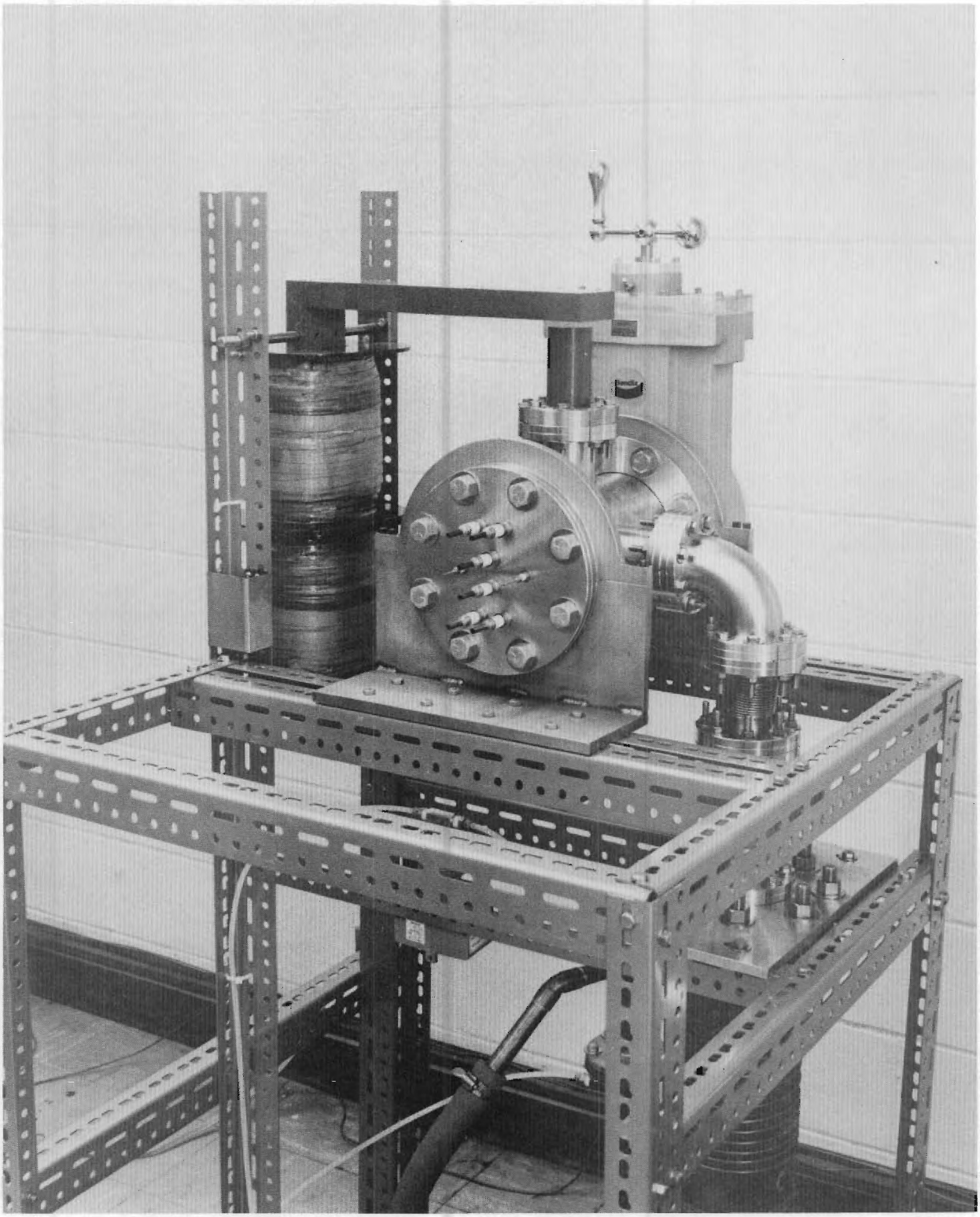

Figure 7. Photograph of the Multiply Charged Ion Source and Associated Vacuum System.

The crossed beam experiment proper is housed in the large vacuum chamber. (See Figure 6.) This housing, which has been used in other work,[20] is 51 cm in diameter and 51 cm high and is pumped with a 15 cm oil diffusion pump and a zeolite trap. An ultimate pressure of 1×10^{-9} Torr can be obtained. Four 15 cm diameter ports, to which beam handling systems can be attached, are placed symmetrically around the chamber. Photon detection optics will be mounted on top of the chamber or when vacuum uv measurements are being made, in a cylindrical housing which mounts over a 15 cm hole in the chamber top.

The collision experiment is expected to be similar in construction to that used in our previous work[25,40,41] with certain significant changes. Since the ion source will be situated far from the interaction region, no problems with stray light from it are anticipated. The electron source will utilize either a magnetically confined low energy beam suitable for work in the low electron energy regime or a dispenser cathode for use in the study of reactions having a higher threshold. The profile will be measured with an L-shaped scanner having coplanar slits and operated by a stepping motor from outside of the experimental chamber. Ion and electron beams will be regulated as was done previously,[25] but a minicomputer will be used to periodically sample the various currents, accumulate signal counts and measure the form factor. It is imperative that this experiment have provision for automatic data acquisition since the low signal levels will require long counting times.

---

[40] F. M. Bacon and J. W. Hooper, Phys. Rev. 178, 182 (1969).

[41] P. O. Taylor and G. H. Dunn, Phys. Rev. A 8, 2304 (1973).

The procedure for absolute calibration has been described in detail by Pace and Hooper[25] and by Taylor and Dunn.[42] Much of the proposed work involves an extension of the procedure to a more difficult wavelength regime. A tungsten strip filament lamp can be used as the primary standard of spectral radiance for wavelengths above about 3000 Å. For shorter wavelengths, the most desirable standard would be the NBS Synchrotron. It would thus be necessary to transfer the calibration to the experiment via intermediate sources and detectors.

It is expected that the initial cross section measurements will be on the 2^3S-2^3P transition in Li^+. Use of this ion will allow separate testing of the collision chamber and the ion beam production/handling system. A high output thermionic source of Li^+ ions can be attached directly to the appropriate chamber port. Other cross sections seheduled for measurement are listed in Table 3. The thin film interference filter for the Li^+ transition has been received and one has been on order for the B^{2+} line.* It is believed that the ion beam system will be operational and some Li^+ excitation data obtained before the end of the proposed next contract period.

---

[42] P. O. Taylor, K. T. Dolder, W. E. Kauppila, and G. H. Dunn, Rev. Sci. Instrum. 45, 538 (1974).

* The thin film interference filters have been on order for about one year and only the Li^+ (5486Å) has as yet been received. Delays of this type are becoming common. A delivery time of nine months has been quoted on pre-drilled steel angle used in the construction of apparatus supports.

Table 3. Tentative List of Cross Sections to be Measured*

Sequence	Transition	Ion	Wavelength (Å)	Estimated Cross Section (cm^2)
He I	$2^3P - 2^3S$	Li II	5486	2.1×10^{-18}
		B IV	2823	2.3×10^{-19}
		C V	2274	1.1×10^{-19}
Li I	$2^2P - 2^2S$	B III	2067	1.2×10^{-15}
		C IV	1549	6.3×10^{-16}
		N V	1240	4.5×10^{-16}

* Measurements will not necessarily be made in order listed. List does not include all cross sections under consideration.

VII. Elastic Momentum Transfer Cross Sections

A quantitative knowledge of the elastic scattering of electrons by atoms and molecules in a gas is basic to the understanding of the electrical properties of a gas or a plasma containing neutral particles. The energy dependence of electron scattering below about one eV is of particular interest in the field of electromagnetic wave propagation in the upper atmosphere[43] and in weakly ionized laboratory plasmas.[44] The measurement of low energy electronic scattering by rare gas atoms is of considerable importance due to a combination of its theoretical implications and the substantial differences which exist in experimentally measured data.

A basic measure of the probability of the occurrence of an elastic electrostatic interaction (collision) between an electron and an atom is the total elastic scattering cross section, σ_t, which has units of area and which varies with relative speed of the two particles. This cross section is the effective area presented by the atom for changing the direction of movement of the electron by any amount. Another cross section is the elastic scattering cross section for momentum transfer, σ_m, which also varies with relative speed. This cross section is the effective area presented by an atom for changing the momentum of the electron. The difference between the two cross sections is, essentially, that σ_t is independent of any angular dependence of the scattering while σ_m is not. For the case in which all scattering angles are equally probable

---

[43] J. M. Anderson and L. Goldstein, Phys. Rev. 100, 1037 (1955).

[44] G. Bekefi, Radiation Processes in Plasmas (John Wiley, 1966), Ch. IX.

$\sigma_m \equiv \sigma_t$. When the scattering is predominantly small angle, $\sigma_t > \sigma_m$. The quantity associated with the cross section which gives the rate at which scattering occurs is the collision frequency ν, which has units of sec^{-1}. The collision frequency is related to the cross section by the formula $\nu = N\sigma V$ where N is the number density of the scatterers and V is the relative speed of the scattered and scattering particles. It is the momentum transfer cross section and collision frequency which enter into calculations of the transport properties of a gas, and hence are the most interesting quantities to measure.

The microwave transient response of a plasma in a uniform magnetic field is the electromagnetic radiation produced by plasma electrons after being subjected to a short pulse of microwave energy at the electron cyclotron frequency. Under the appropriate experimental conditions, the decay in time of this radiation is due to the dephasing effects on the electron oscillations of the electrostatic interaction of the electrons with the various plasma constituents. Above a critical value of gas pressure and for sufficiently low plasma density, the transient response decay is determined predominantly by the scattering of electrons by neutrals and is exponential in character. Under these conditions, the decay rate is a measure of the electron-neutral momentum transfer collision frequency. The energy of the electrons is determined by the applied microwave pulse strength. The present experimental apparatus measures the transient response decay rate as a function of applied microwave pulse strength. These data are converted to collision frequency as a function of energy by a straightforward process.

In the apparatus, a plasma tube is evacuated and refilled with the

gas to be studied to a pressure between 5 and 50 millitorr. An electron beam is repetitively pulsed through the gas to form a low temperature plasma by electron impact ionization. A highly uniform static magnetic field is applied along the axis of the plasma tube. The plasma tube is inserted into an S-band waveguide structure in such a manner that the electric field vector of the dominant waveguide mode is normal to the direction of the static magnetic field vector. The waveguide structure is an E-plane cross configuration, and the plasma tube is inserted along the axis of symmetry of the cross. The input microwave pulse is a ten nanosecond burst of a 2.7 GHz carrier obtained by bandpass filtering the output of a fast rise time d.c. pulser and amplifying with a TWT amplifier. The microwave pulse is divided into two nearly equal pulses by a hybrid tee and applied to two opposing ports of the cross. The transient response signal is measured through the orthogonal set of ports. The two transient response signal components are combined for measurement in a second hybrid tee. By appropriately adjusting the relative phases of the applied pulses and the transient response signal components, a high degree of isolation is obtained between the applied pulse circuit and the transient response measurement circuit.

The transient response is amplified by a TWT amplifier and square law crystal detected. The video signal is amplified and processed to obtain the logarithmic response. The slope of the logarithmic response corresponds to the measured collision frequency. The electron energy is varied by varying the amplitude to the applied microwave pulse. The

---

[45] L. S. Frost and A. V. Phelps, Phys. Rev. 136, A1538 (1964).

collision frequency is absolutely calibrated while the electron energy is calibrated from the position of the Ramsauer minimum of argon.

The preliminary data for argon is presented in Figure 8. The swarm data of Frost and Phelps is presented for comparison. This preliminary transient response data is the average of several sets of data taken while developing the experimental technique, and as such serve only to demonstrate the feasibility of obtaining accurate measurements from the apparatus. A computer technique for correcting the experimental data for the non-uniform character of the microwave excitation pulse over the plasma volume is currently under development. The results of a tentative form of this correction are presented along with the uncorrected data to show the general effects of such a correction.

It is expected that the final experimental data will be taken in the next several weeks. The final report on this research should be completed in the next two months.

VIII. Publications During the Contract Period

The following paper based on this research was published during the contract period:

M. O. Pace and J. W. Hooper, "Absolute Experimental Cross Sections for the Excitation of Barium Ions by Electron Impact," Phys. Rev. A 7, 2033 (1973).

Three papers based on this research are now in preparation and will be submitted prior to the end of the current contract period. These are as follows:

i) D. A. McPherson, R. K. Feeney, and J. W. Hooper, "Microwave Transient Response Measurement of the Momentum Elastic Scattering Cross Section for Electrons in Argon Gas," to be submitted to Phys. Rev.

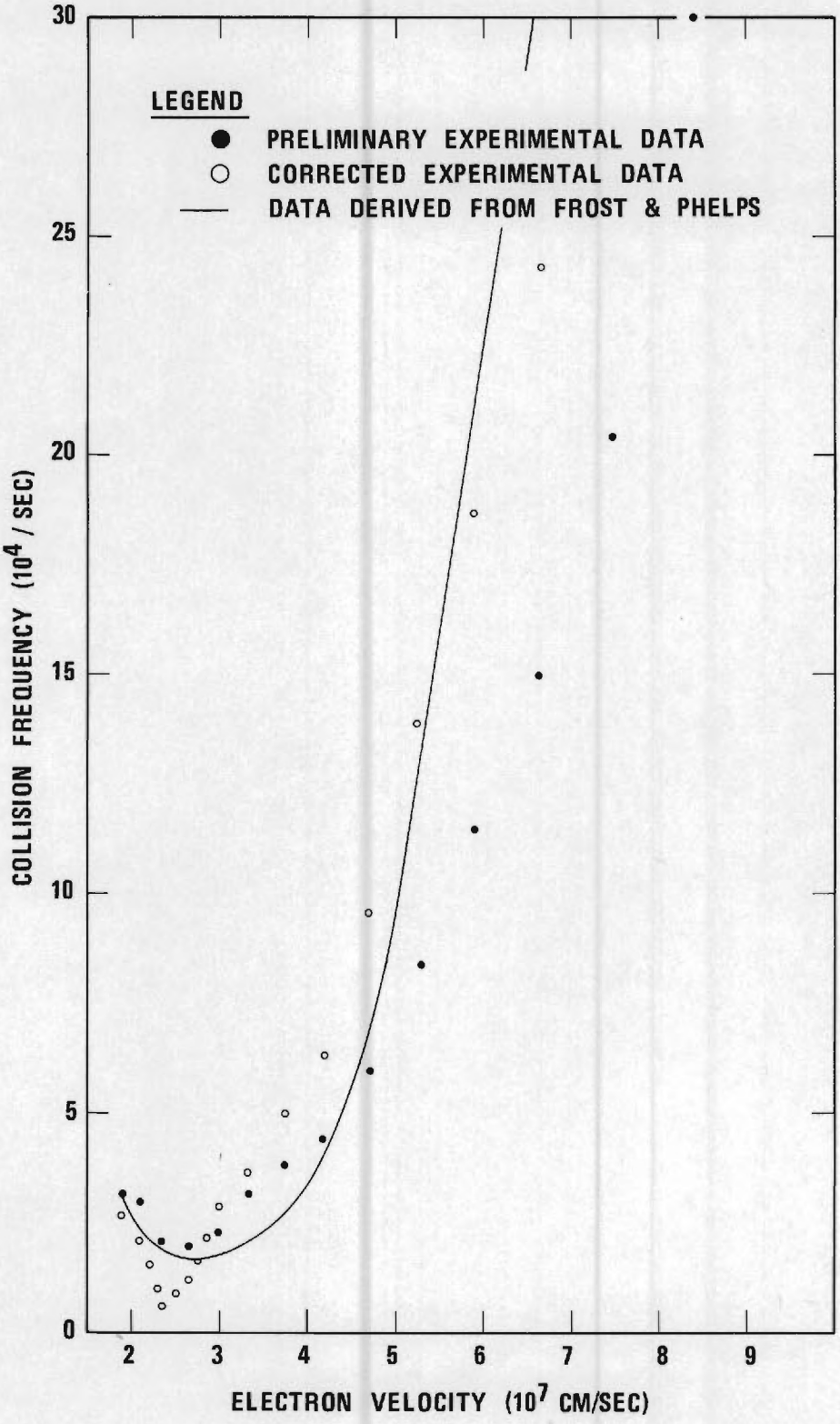

Figure 8. Elastic Momentum Transfer Collision Frequency of Electrons in Argon Gas. Data Normalized to 1 mTorr and 0°C.

ii) T. F. Divine, R. K. Feeney, and W. E. Sayle, "Absolute Experimental Cross Sections for the Ionization of Tl^+ Ions by Electron Impact," to be submitted to Phys. Rev.

iii) R. K. Feeney and W. E. Sayle, "Thermionic Sources of Positive Ions for Use in Collision Experiments," to be submitted to Rec. Sci. Instrum.

IX. Travel During the Contract Period

R. K. Feeney and W. E. Sayle attended the 1st International IEEE Conference on Plasma Science at Knoxville, Tennessee. R. K. Feeney made several trips to Oak Ridge National Laboratory, and one trip to Rensselaer Polytechnic Institute of connection with this research program.

X. Incident Report

There have been no incidents for which a report is required, during the performance of the research under this contract in the present reporting period.